Heinke

Thanks

Thermal Radiation from Neutron Stars in Globular Clusters: Constraints on Mass and Radius?

TWO PARTS: GLOBS, 47 Tuc

Or, Two Unpleasant Surprises about H-atm B=0 models

Craig Heinke

Harvard University

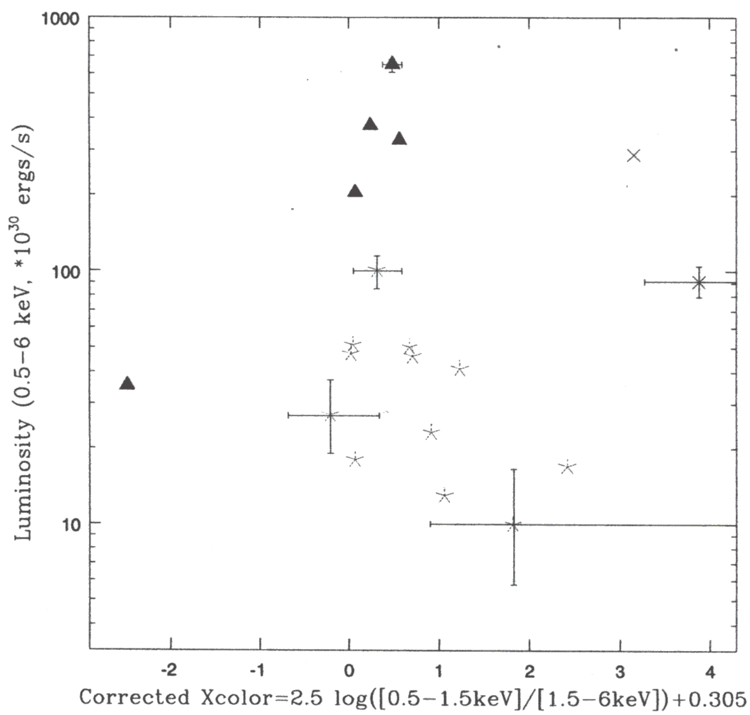
Globular Cluster 47 Tucanae from Earth

Photo Credit: Anglo–Australian Observatory, D. Malin

Classifying X–ray Sources: M80

X–ray CMDs (Lx vs. 0.5–1.5 keV cts/1.5–6 keV cts ratio) separate some classes of source by luminosity and broad spectral shape.

"True–color images" use 0.5–1.2 keV, 1.2–2 (or 2.5) keV, 2–6 keV



Heinke et al. 2003a

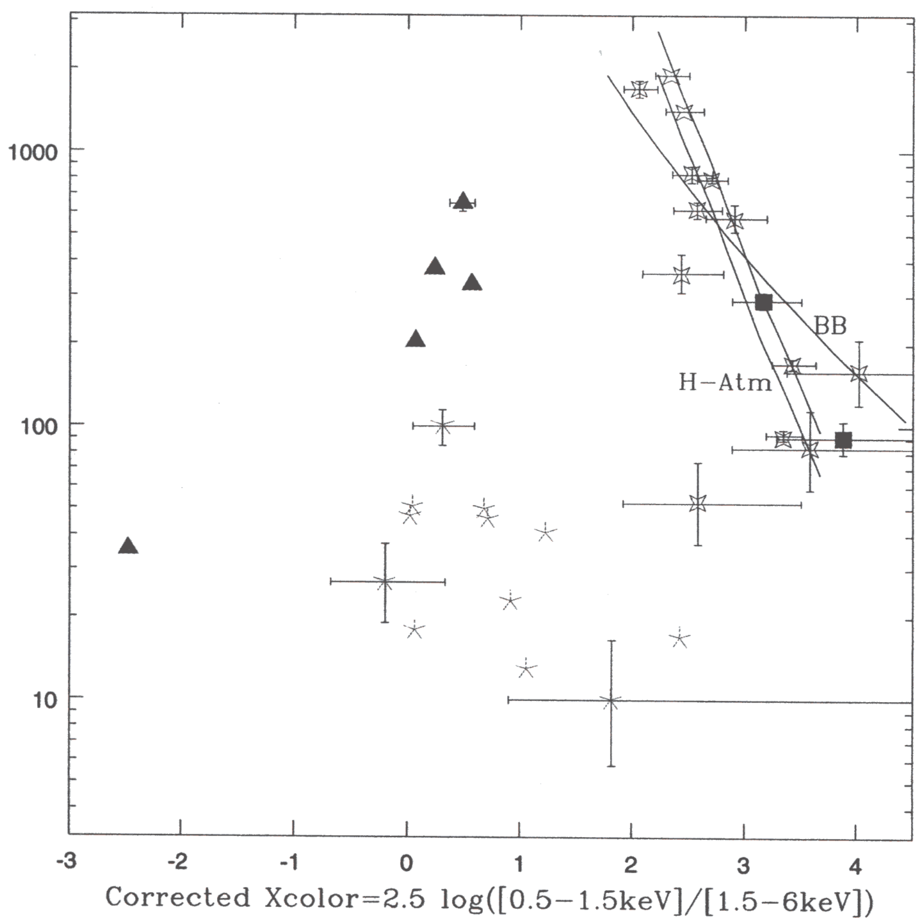
)ptical studies of hard sources, log Lx>32, in 47 Tuc, NGC 6397, ŀGC 6752 (e.g. Edmonds et al. 2003) indicate nearly all are ataclysmic variables.

.uminous soft X–ray sources identified as quiescent LMXBs (qLMXBs) ›y similarity of spectra to H–atmosphere predictions (Grindlay et al. :001, Rutledge et al. 2001, Heinke et al. 2003a, c).

'ainter sources a mixture of millisecond pulsars, active binaries, and aint cataclysmic variables, requiring optical and radio followup.

Quiescent LMXBs

Standardized (reddening–corrected) X–ray CMD.



X–rays from quiescent LMXBs generally consistent with 10–12 km radius, hydrogen–atmosphere neutron stars.

Fixed–R blackbody predictions differ from observations, supporting H–atmosphere models.

M80 CMD (Heinke et al. 2003b) with quiescent LMXBs from other clusters ☆ .

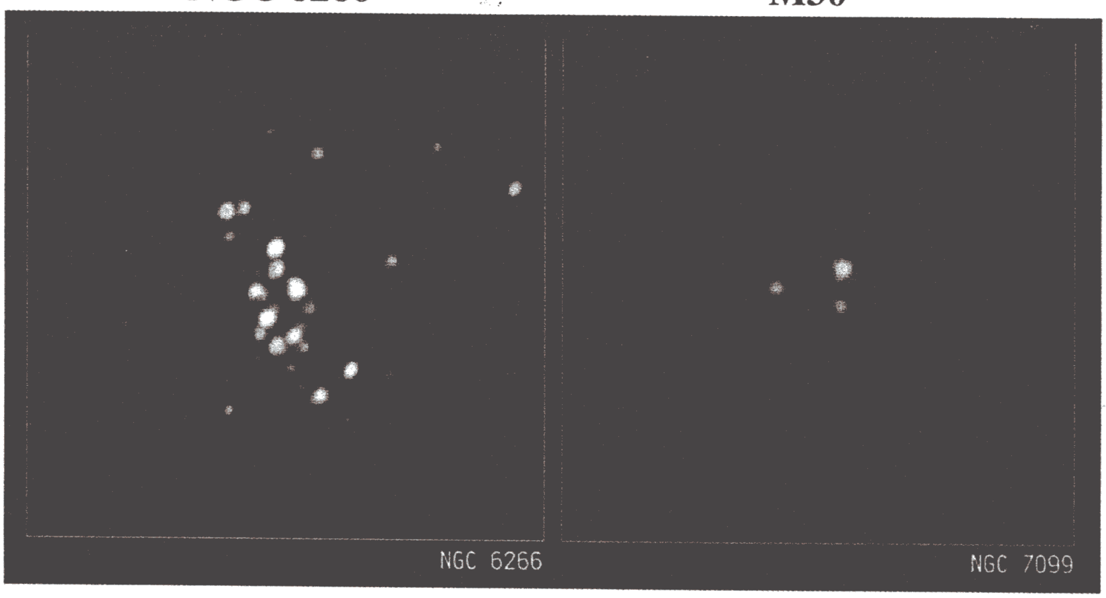
Hard nonthermal (accretion–related?) component seen in several quiescent LMXBs in field with recent outbursts. Globular cluster quiescent LMXBs only show this component if they have been recently active (Heinke et al. 2003c).

X–ray Images of Globular Clusters

Distance!
Not All Clusters!

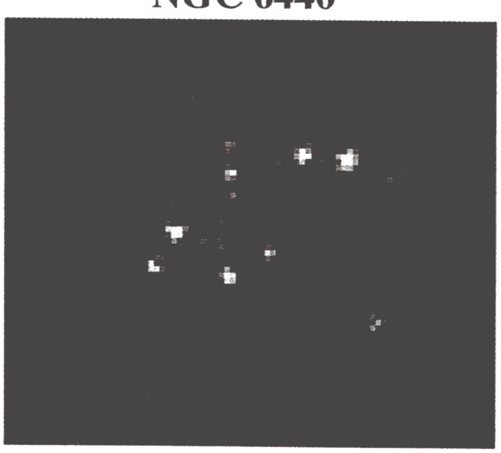
27 qLMXBs identified in globular clusters
Distribution suggests dynamical formation, total ~100
Log Lx (0.5–2.5 keV) in range 31.7–33.3
General lack of variability

NGC 6266 **M30**



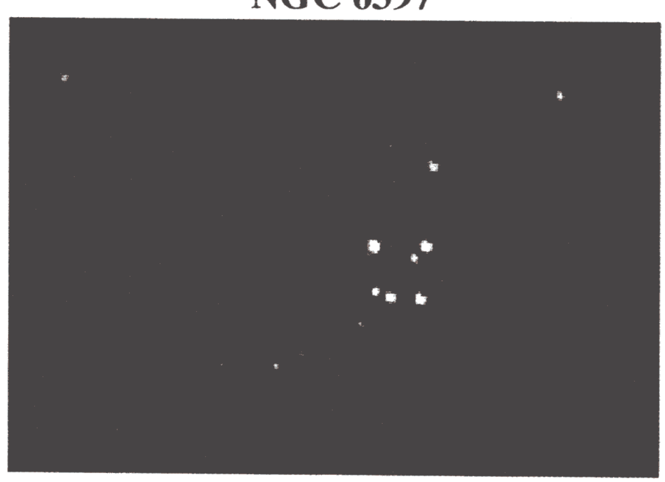
NASA/CXC/D. Pooley, MIT/H. Cohn & P. Lugger, Indiana

NGC 6440



Pooley et al. 2002

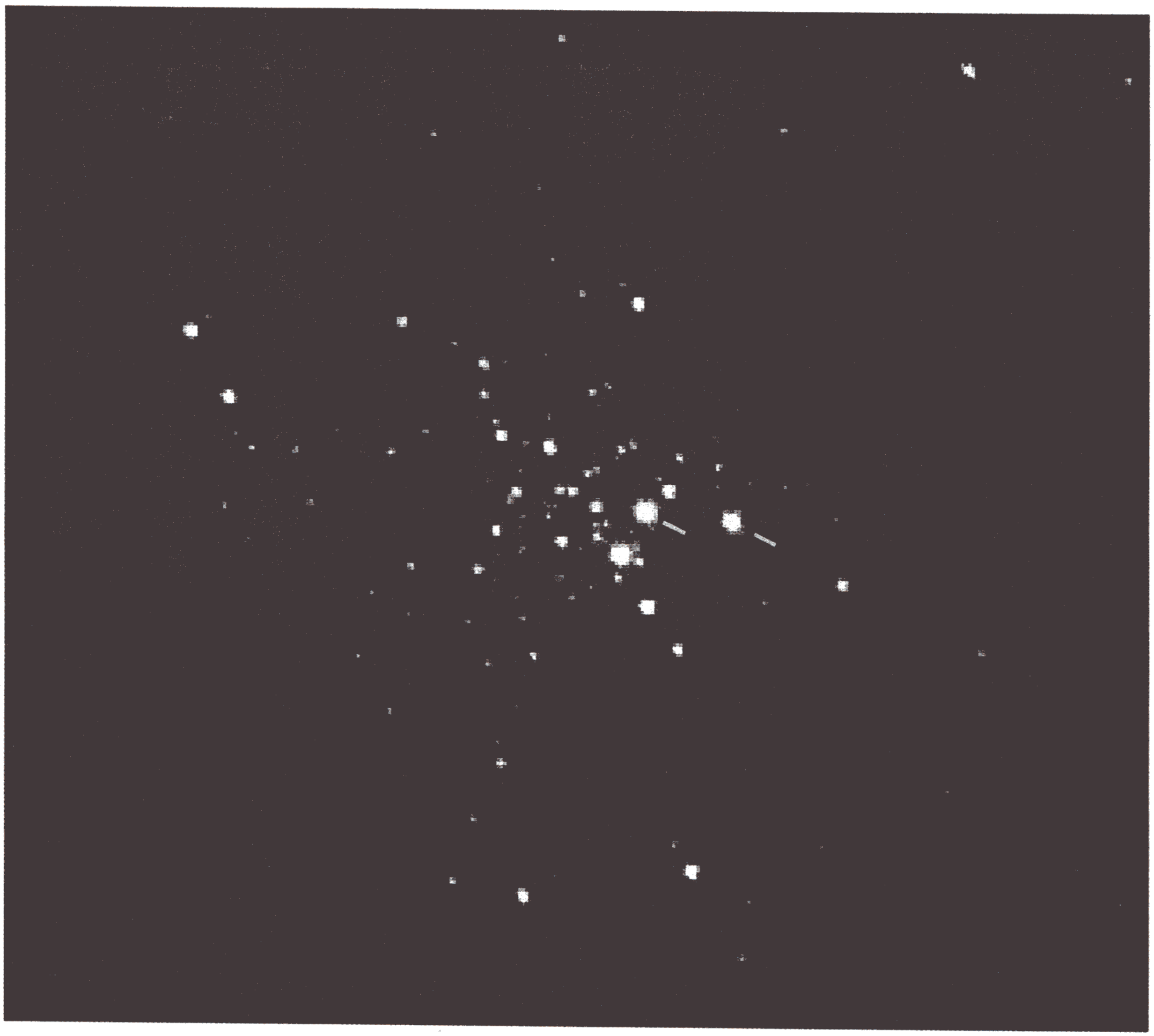
NGC 6397



Grindlay et al. 2001

Deepest Globular Cluster X–ray Survey: 47 Tuc

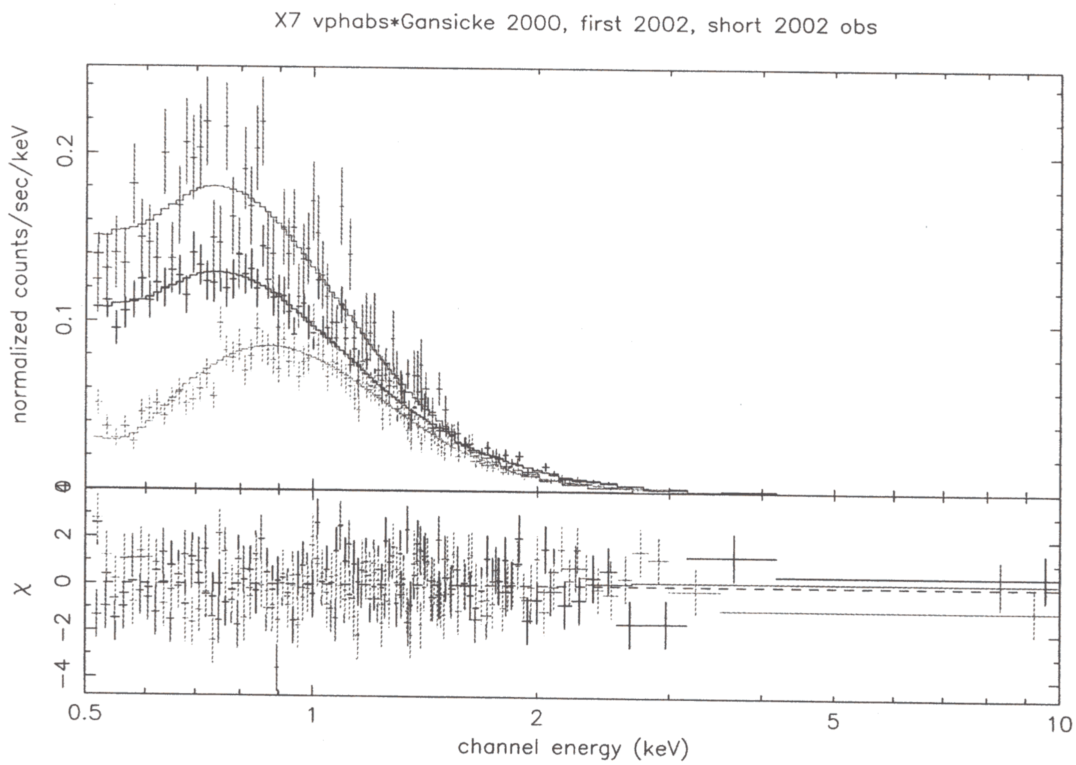
72 ksec in 2000 with Chandra ACIS–I.
286 ksec in 2002 with more sensitive Chandra ACIS–S,
20 ksec in subarray to reduce pileup of bright sources.



Unprecedented resolution and sensitivity allows detection of 300 sources within half–mass radius, detailed spectra of bright sources including two qLMXBs, X5 and X7, with log Lx~33.

H Atmosphere Fit to X7 Spectrum

X7 shows no variability within 2002 (or 2000) dataset.
Spectral change between 2000 and 2002 indicates decreased N_H
Spectral modeling uses pileup model, photoelectric absorption with 47 Tuc or solar metallicity, and H atmosphere models.



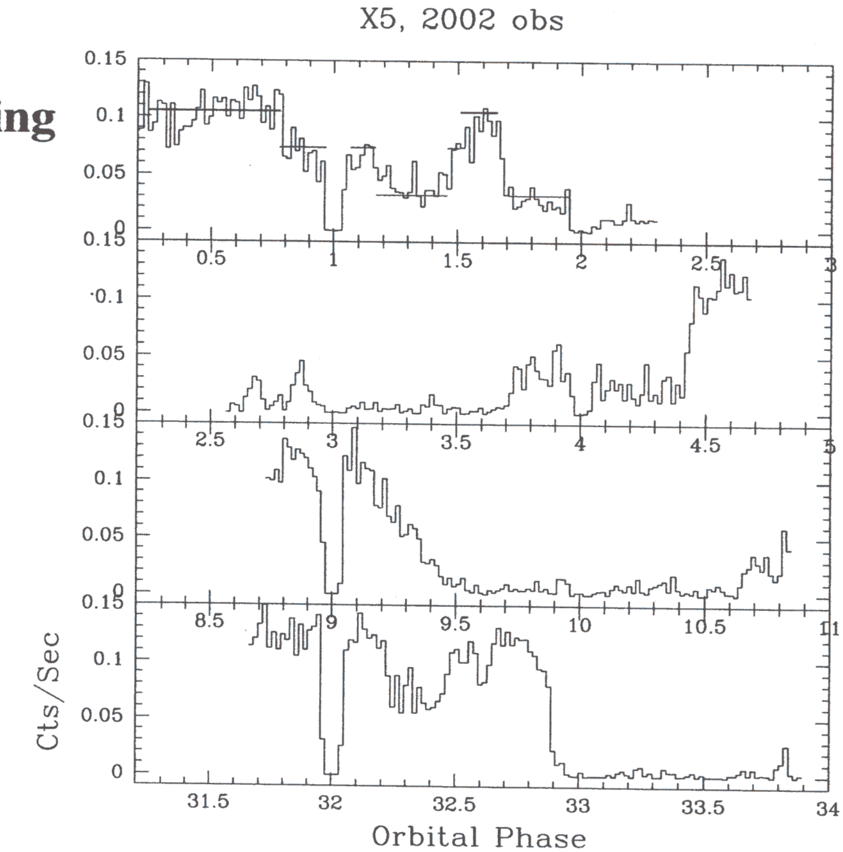
Data shown from: 2000 (ACIS−I detector with less sensitivity), one 2002 long obs, four short 2002 obs (with reduced pileup).

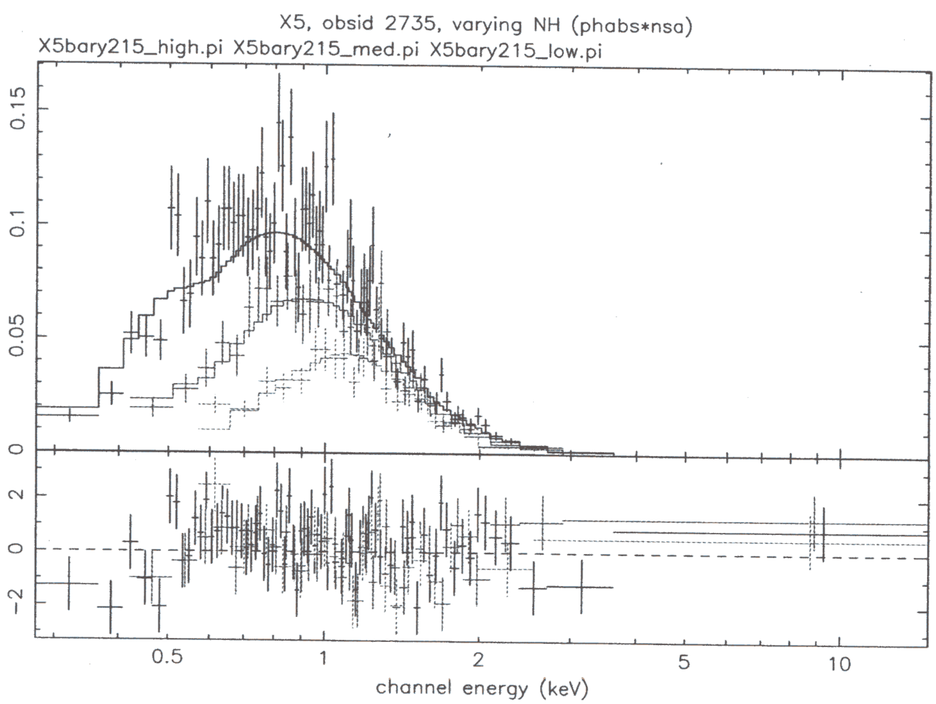
Excellent fits to overall data with no additional features (χ^2_ν=1.02, 527 d.o.f.); no need for edge suggested by Heinke et al. 2003a.

Dramatic Eclipses and Dips from X5

X5's lightcurve shows dramatic variability, including eclipses and severe dipping at all orbital phases.

Such extreme variability indicates strong activity in the quiescent disk, never identified before.





We extract spectra from high, medium, and low flux states.

Spectra taken from different flux levels are consistent with variations in N_H alone, with $\chi^2_\nu = 1.07$ for 411 d.o.f.

cheinke 16-Jul-2003 16:48

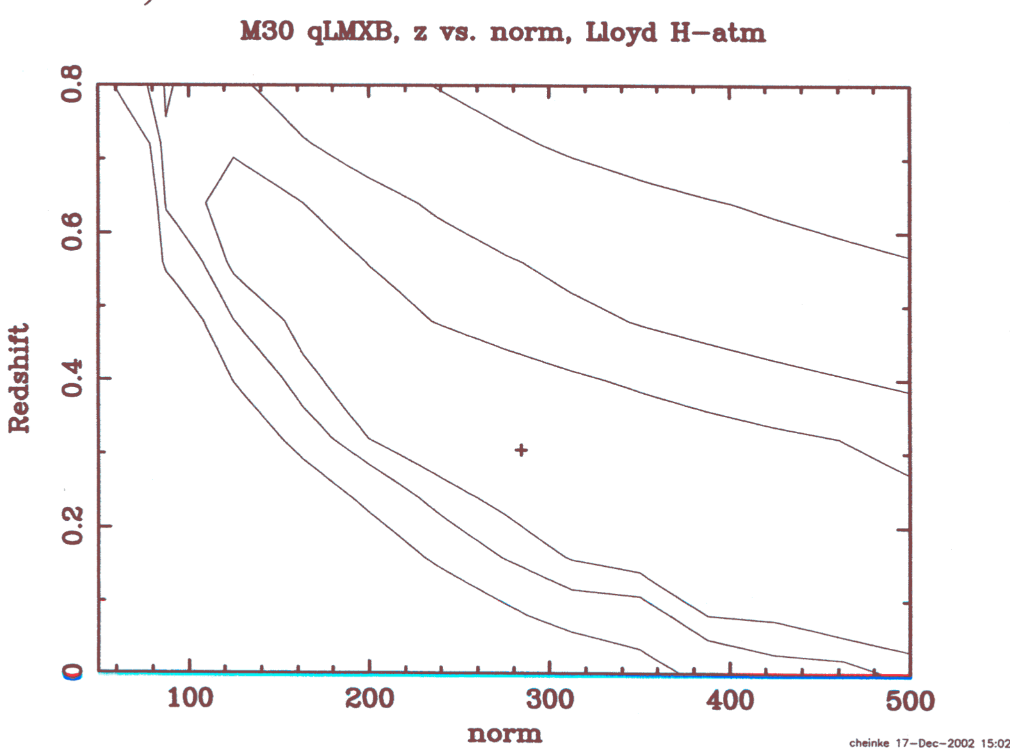
Constraining Mass and Radius with qLMXBs

Similar method to Rutledge & coworkers.
Assume isotropic emission through H atmosphere.
(Anisotropy could allow larger M & R, but not smaller.)
Pure H expected for deep crustal heating (Brown et al. 2001).

Hope to constrain radius by fitting spectrum, but suffer degeneracy with gravitational redshift, producing allowed region in M–R space.

Three H–atmosphere models available:
Zavlin et al. (1996), parameters M, R, D, Teff
Gansicke et al. (2002), parameters Teff, z, norm (αR/D)
Lloyd et al. (2003), parameters Teff, z, norm (αR/D)

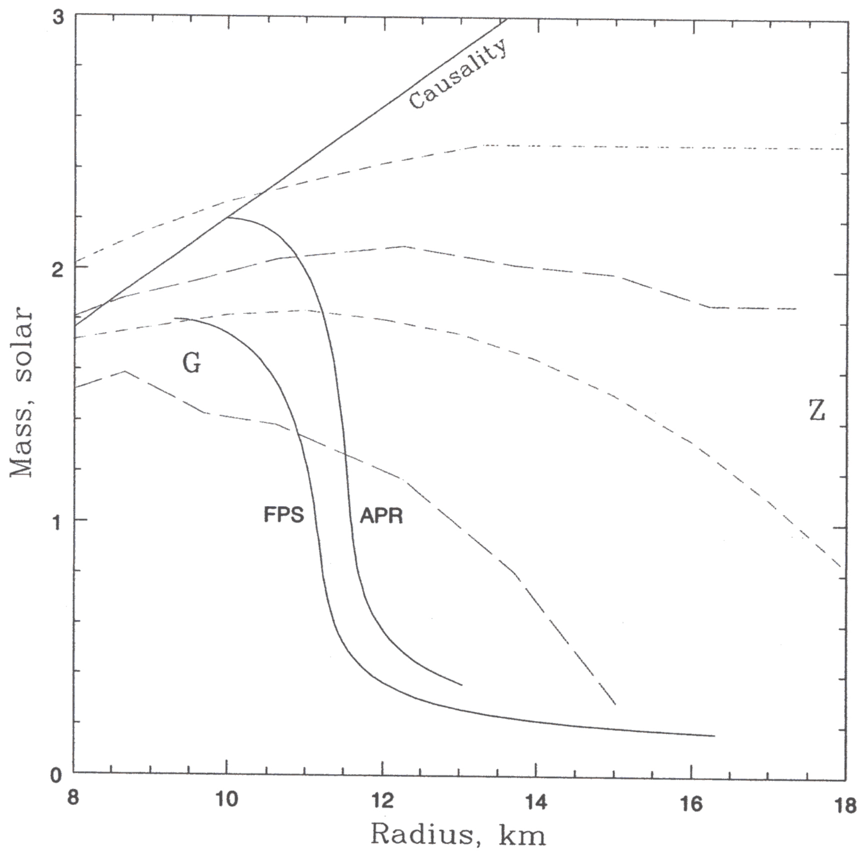
Fix D for Zavlin, produce M, R contours directly.
Produce z, norm contours for others, compute M from z, R.



Example:
Lloyd model,
1σ, 90%, 99%
contours,
fitting
M30 qLMXB.

M–R Constraints from X5 Spectrum

Combining pieces of near–constant flux, from 2000, 2002, produces interesting constraints on M, R.



90% contour from Zavlin model, rough best fit "Z".

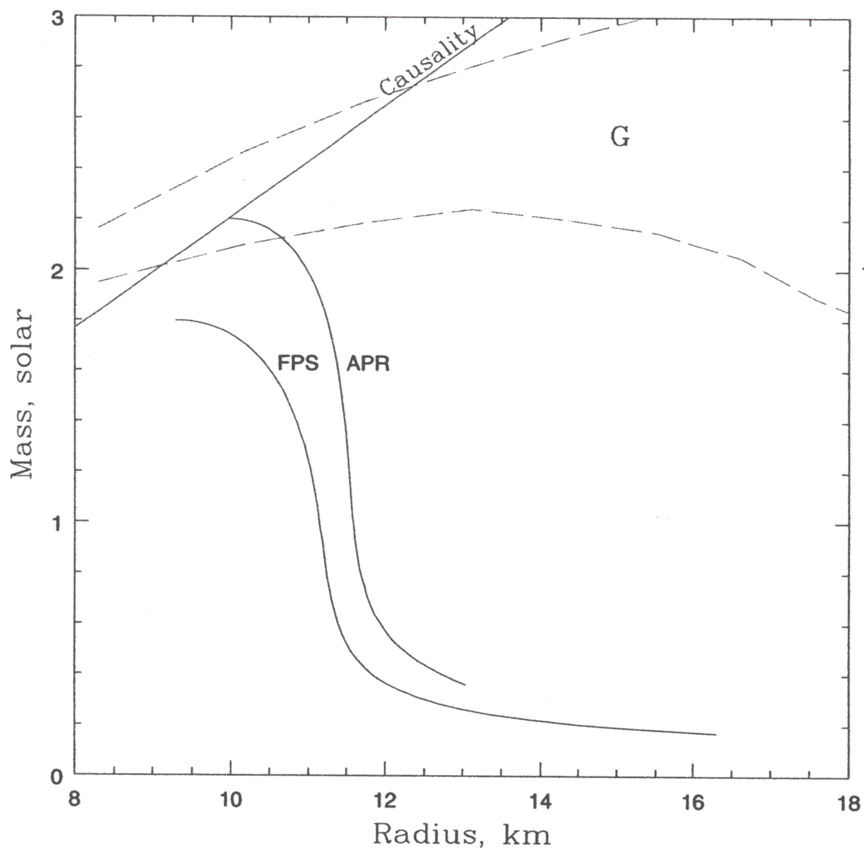
90% contour from Gansicke model, rough best fit "G".

FPS and APR model NS EOSs labeled, and causality limit.

Marginally rules out M=1.4 if R<10 km.

M–R Constraints from X7 Spectrum

Combining X7 spectra from 2000, 2002, and short 2002 obs allows stringent constraints on M, R.



Gansicke model requires M>2 Msun for 10<R<16 km.

Zavlin model requires higher mass, runs into 2.5 Msun limit.

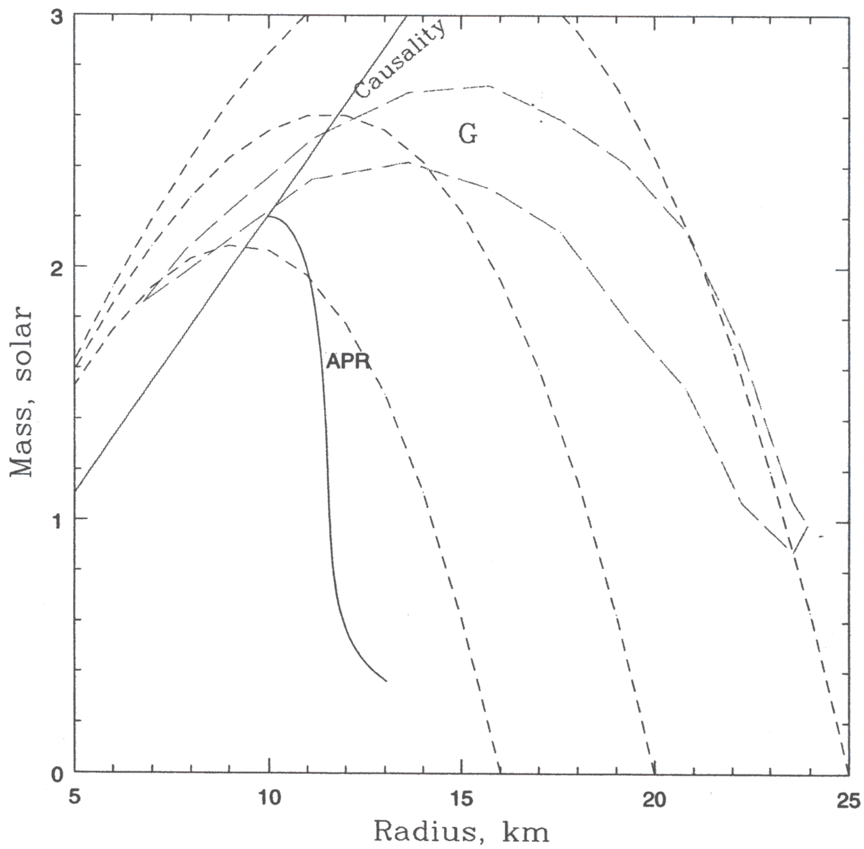
If this constraint is correct, a very stiff EOS is required, and softening by pions, hyperons, free quarks are excluded.

R, M contours do not follow R_inf

For a blackbody, measuring the color temperature directly gives R_inf=R(1+z), which defines contours in M, R.

However, R–M contours for H–atm fits of qLMXBs do not follow R_inf contours.

X7 Gansicke contours, fixing N_H R_inf contours overlaid.



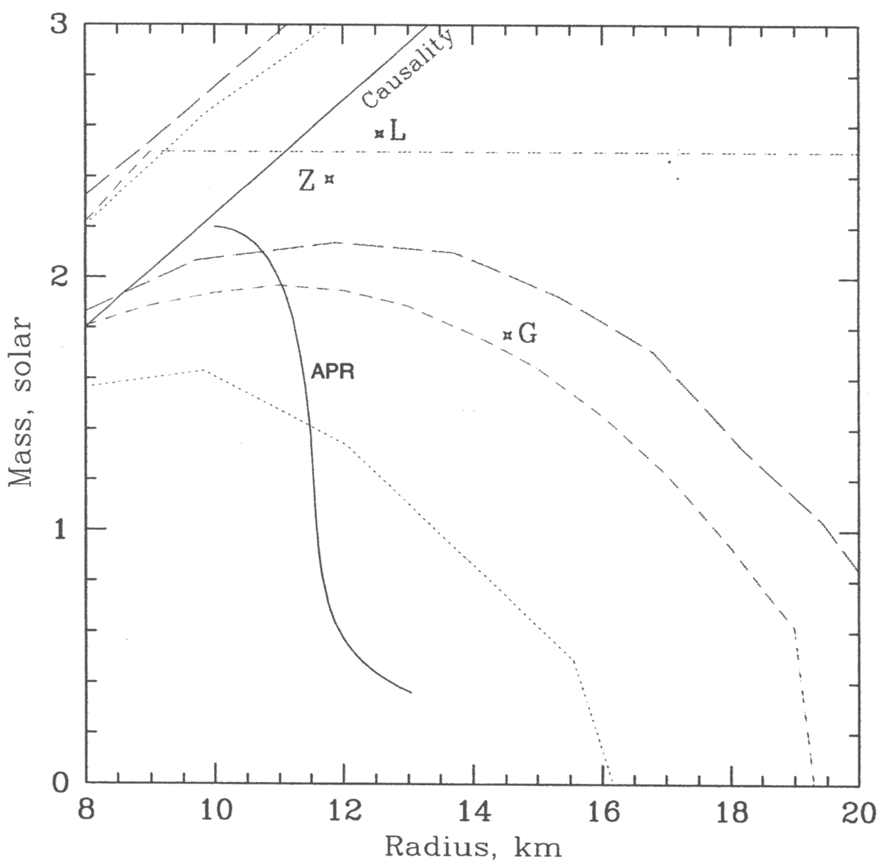
Probable explanation: The relation between Tcolor and Teff is not constant for H–atmosphere models.

Additional qLMXB Constraints

Globular cluster qLMXBs offer advantages of known distance (to ~10%), and little to no hard powerlaw component.

M30 qLMXB also shows interesting constraints;

M>1.4 Msun if R<11.5 km (Lugger et al. 2003, in prep).



Data from ωCen and NGC 6397 qLMXBs promising, but not as constraining.

Conclusions

Globular cluster qLMXBs show thermal radiation from hydrogen atmospheres, with no evidence (features, variability, hard nonthermal components) for continuing active accretion.

Three qLMXBs provide interesting constraints upon the mass and radius of neutron stars. X7 requires a mass greater than 2.0 solar masses for $10<R<16$ km. This constraint requires a very stiff NS EOS.

I thank J. Grindlay, D. Lloyd, P. Edmonds, and L. Bildsten for discussions. This work supported by NASA.